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The properties and evolution of low surface brightness galaxies

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Document Version

Publisher's PDF, also known as Version of record

Publication date:

1997

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Blok, W. J. G. D. (1997). *The properties and evolution of low surface brightness galaxies*. s.n.

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Discussion: Cold Dark Matter

S.S. McGaugh & W.J.G. de Blok

The rotation curves of LSB galaxies are not consistent with the standard theory of Cold Dark Matter. The halos predicted by this theory are more concentrated than can be accommodated by the data. The LSB rotation curves can be reasonably explained by assuming an open Universe with $\Omega_0 \sim 0.3$.

GALAXIES form from primordial density fluctuations. These density fluctuations can be seen imprinted on the 3 K microwave background. Observations show that the microwave background fluctuations are extremely small. The only way to get from the very small density fluctuations then, to the clumpy universe today was to introduce a dark matter component which only interacts gravitationally, and does not respond to radiation pressure. This form of dark matter is composed of dynamically cold massive particles, hence the name Cold Dark Matter, or CDM. Usually imagined to be some hypothetical fundamental particle (e.g., WIMPs or axions), CDM could also be massive black holes or some other entity which only interacts gravitationally with the rest of the Universe. As it does not respond to radiation pressure, it can begin to clump and form structure early without leaving too much of an imprint on the microwave background.

10.1 Navarro Halos

Most of the investigations into structure formation and evolution have been performed using N -body models. An important discovery on the structure of halos in CDM was made by Navarro et al. (1996) and Cole & Lacey (1996); see also Dubinski & Carlberg (1991). They show that individual CDM halos as simulated in numerical N -body experiments have a universal structure

profile. These take the form

$$\rho_{CDM}(R) = \frac{\rho_i}{(R/R_s)(1 + R/R_s)^2}$$

where R_s is the characteristic radius of the halo and ρ_i is related to the density of the universe at the time of collapse. These parameters are not independent and are set by the cosmology. The concentration of the resultant halo is given by the concentration parameter $c = R_{200}/R_s$. R_{200} is the radius where the density contrast exceeds 200, roughly the virial radius. This establishes a clear expectation value for the mass distribution and resultant rotation curves of CDM halos, which are

$$V(R) = V_{200} \left[\frac{\ln(1 + cx) - cx/(1 + cx)}{x[\ln(1 + c) - c/(1 + c)]} \right]^{1/2}, \quad (10.1)$$

where $x = R/R_{200}$ (Navarro et al. 1996). The velocity V_{200} is characteristic of the halo, and is defined in the same way as R_{200} . The halo rotation curve is thus specified by two parameters, V_{200} and c , which give the total halo mass and the degree of concentration of that mass.

10.2 LSB & CDM

Low surface brightness galaxies are a good place to test this CDM halo prediction, as their disks are dynamically insignificant: the rotation curves provide a direct map of the dark mass distribution. The strongest test is of course done with the lowest surface brightness galaxy with the best resolved rotation curve. Surface brightness is important because it is related to the rate of rise of

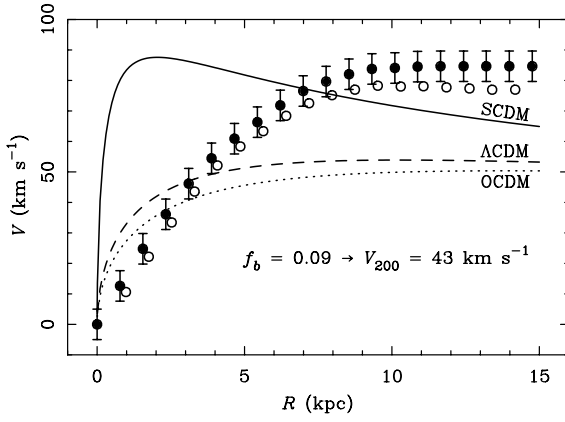


FIGURE 10.1— The rotation curve of F583-1 compared with the form predicted for appropriate CDM halos (Navarro et al. 1996). The solid points are the observed rotation curve, while the open points are the rotation curve of the dark matter with the baryonic component subtracted from the total. The open points have been offset slightly in R for clarity, as the baryons contribute very little. Lines show the predictions of various cosmologies (Table 10.1) assuming $f_b = 0.09$, the value indicated by clusters.

the rotation curve which constrains the concentration parameter. Resolution is important because we wish to test the shape of the rotation curve specified by Eq. 10.1. The galaxy which best suits these requirements is F583-1.

Before testing, we need to remove the influence of the known baryonic component and isolate the dark matter. This is done by assuming a maximum disk stellar M/L for the disk (de Blok & McGaugh 1997) and subtracting the dynamical contribution of the gas and the stars from the rotation curve. Both the observed and the corrected rotation curves are shown in Fig. 10.1, where it is clear that the assumption about the stellar disk mass is not a critical one.

To compute the model rotation curve one needs to specify an appropriate c and V_{200} . The concentration parameter depends on the cosmology, for which we consider several possibilities using the halo characterization code provided by Navarro (priv. comm.). We will refer to three basic cases: standard CDM with $\Omega = 1$ (SCDM), open CDM with $\Omega = 0.3$ (OCDM), and a flat Λ -dominated cosmology with $\Omega_\Lambda = 0.7$ (Λ CDM). Lower Ω generally results in lower c , as does lower H_0 . The latter is not a strong effect, so we retain a fixed $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Other parameters matter fairly little, except the normalization of the power spectrum which we fix to the COBE observations. Adopting a different normalization, like that for rich clusters, has the fairly minor effect of interchanging the relative concentrations of the OCDM

TABLE 10.1— Concentration c

Model	$f_b = 0.09$	$V_{200} = 80$
SCDM	60	52
OCDM	9	8
Λ CDM	12	11

and Λ CDM cases: OCDM is the least concentrated model with a COBE normalization, but Λ CDM is the least concentrated for a lower normalization. This distinction is fairly modest but might matter as we shall see that the observations require low c .

The last item needed is an estimate of V_{200} or the mass of the halo, which is also a minor factor in determining c . This can be done in a variety of ways. One is to use the observed baryonic disk mass as an indicator of the halo mass. The mass of the disk is reasonably well constrained by the maximum disk solution ($M_* = 4.5 \times 10^8 M_\odot$) and the fact that most of the baryons are in directly observable atomic gas ($M_{\text{gas}} = 1.4 M_{\text{HI}} = 2.4 \times 10^9 M_\odot$). These give a total of $M_{\text{bar}}(\text{F583-1}) \approx 2.9 \times 10^9 M_\odot$ which can be combined with a baryon fraction to give a halo mass. The baryon fraction is thought to be well measured by rich clusters of galaxies, giving $f_b \approx 0.09$ (for $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-2}$; e.g., White & Fabian 1995). This then implies a halo mass of $M_H \approx 3.2 \times 10^{10} M_\odot$.

The concentration indices derived for these cases are listed in Table 10.1 and the results plotted in Fig. 10.1. The SCDM model overpredicts the rate of rise of the rotation curve severely. The less concentrated OCDM and Λ CDM models do likewise, but to a lesser extent. All predict too small an asymptotic velocity, as the halo mass appropriate for the observed baryon mass gives $V_{200} = 47 \text{ km s}^{-1}$ when $V_c = 84 \text{ km s}^{-1}$.

Part of the problem here is the well known failure of CDM models to simultaneously match the observed luminosity density and the normalization of the Tully-Fisher relation (e.g., Heyl et al. 1995; Frenk et al. 1996). Let us therefore try another approach. Navarro (1996a) suggests that the Tully-Fisher relation arises because $V_c \approx V_{200}$ (though note that Navarro 1996b found that halo mass was not well correlated with optical luminosity). By adopting $V_{200} = 80 \text{ km s}^{-1}$, we should at least come close to matching the outer portion of the rotation curve. This implies a much more massive halo, $M_H \approx 1.2 \times 10^{11} M_\odot$, and a correspondingly lower baryon fraction, $f_b = 0.015$.

This exercise again fails to fit the SCDM data (Fig 10.2). The rate of rise and the amplitude of the Λ CDM model are again too large. Only the

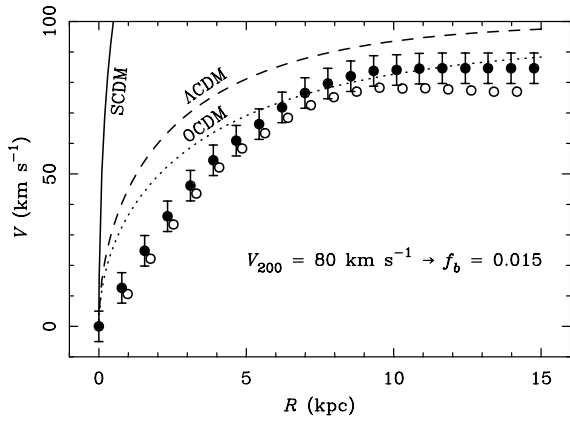


FIGURE 10.2— As Fig. 10.1, but now with V_{200} fixed at a value $V_{200} = 80 \text{ km s}^{-1}$ (i.e., a Tully-Fisher normalization which ignores the consequences for the baryon fraction).

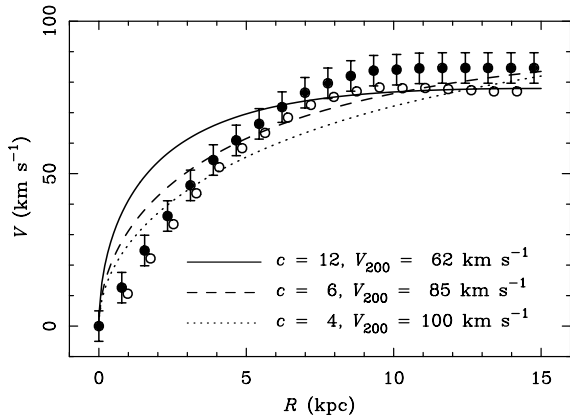


FIGURE 10.3— As Fig. 10.1, but here it is simply tested whether any Navarro et al. (1996) profile can fit the observations, regardless of cosmology. Even treating both c and V_{200} as completely free parameters, no fit can be obtained. CDM predicts the wrong shape for galaxy halo density profiles.

OCDM model comes close to fitting the data. It remains to be seen whether the bad fit in the inner parts is due to mild beam-smearing, or whether it is a true defect of OCDM. More fits, and higher resolution data should help out here. Apparently, the Tully-Fisher relation does not arise from a simple equation of V_c with V_{200} .

Is it possible to produce a *good* fit of the data with Eq. 10.1 at all? The answer is that it is hard to do so. Fig. 10.3 gives several examples which come reasonably close by choosing c and V_{200} without regard to their cosmological origins. The model with $c = 12$ gives a flat rotation curve for the outer points, but overpredicts the inner rotation. Lower concentration models can fit the interior points, but at the expense of producing a large positive slope in the outermost points.

It has already been noted (Moore 1994; Flores & Primack 1994) that the steep interior density distribution ($\rho_{\text{CDM}}(R) \propto R^{-1}$ at small R) predicted by CDM is inconsistent with the observations of dwarf galaxies. These dwarfs are all low surface brightness systems, which is the reason they are relevant. This problem of the shape of the rotation curves is also clear in our data. We therefore confirm and extend the results of Moore (1994) and Flores & Primack (1994).

A solution which is often invoked to make the halo rotation curves less steep, and more reminiscent of an isothermal sphere halo, is mass redistribution. In this case, we presume the initial halo profile was “correct,” but that subsequent processes somehow altered the mass distribution into its observed form. This might happen, but it eliminates the predictive value of the model.

There are two basic possibilities for mass redistribution. Since the CDM is well behaved, both invoke interactions with the less predictable baryonic matter. One possibility is that the dissipation of baryons draws the dark matter further in (sometimes called the adiabatic response of the halo to the disk). This should happen at some level (Dubinski 1994), but it makes the problem worse: halos which are initially too concentrated become even more so.

The other possibility is just the opposite: somehow, the baryons manage to expel mass, leading to a more diffuse mass distribution. A frequently invoked mechanism is feedback due to violent star formation. This requires a small mass of stars and gas to have a dramatic impact on the distribution of the dominant dark mass, with which they can only interact gravitationally. Though rather vague, this scenario does make one clear prediction: galaxies explode and gas is lost. However, the dim galaxies for which the need for mass redistribution is most severe are in fact very gas rich (McGaugh & de Blok 1997). It is therefore very unlikely that baryonic outflows can play a significant role in redistributing the dark matter.

10.3 Summary

SCDM can be ruled out. To save SCDM two unlikely processes are required. First, the baryon fraction in LSB galaxies must change by an order of magnitude from the value found in clusters. Second, the dark matter distribution must be radically changed from a Navarro et al. (1996) profile (Eq. 10.1) to something close to an isothermal sphere.

OCDM produces the most acceptable fit to

these data (see also Navarro 1996a; Pickering et al. 1997), and requires $\Omega_0 \simeq 0.3$. Apparently LSB galaxies tell us we live in an open Universe.

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